

Secure Wireless Communication and Optimal Power¹ Control under Statistical Queueing Constraints

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Abstract

In this paper, secure transmission of information over fading broadcast channels is studied in the presence of statistical queueing constraints. Effective capacity is employed as a performance metric to identify the secure throughput of the system, i.e., *effective secure throughput*. It is assumed that perfect channel side information (CSI) is available at both the transmitter and the receivers. Initially, the scenario in which the transmitter sends common messages to two receivers and confidential messages to one receiver is considered. For this case, *effective secure throughput region*, which is the region of constant arrival rates of common and confidential messages that can be supported by the buffer-constrained transmitter and fading broadcast channel, is defined. It is proven that this effective throughput region is convex. Then, the optimal power control policies that achieve the boundary points of the effective secure throughput region are investigated and an algorithm for the numerical computation of the optimal power adaptation schemes is provided. Subsequently, the special case in which the transmitter sends only confidential messages to one receiver, is addressed in more detail. For this case, effective secure throughput is formulated and two different power adaptation policies are studied. In particular, it is noted that opportunistic transmission is no longer optimal under buffer constraints and the transmitter should not wait to send the data at a high rate until the main channel is much better than the eavesdropper channel.

I. INTRODUCTION

Security is an important consideration in wireless systems due to the broadcast nature of wireless transmissions. In a pioneering work, Wyner in [1] addressed the security problem from an information-theoretic point of view and considered a wiretap channel model. He proved that secure transmission of confidential

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messages to a destination in the presence of a degraded wire-tapper can be achieved, and he established the secrecy capacity which is defined as the highest rate of reliable communication from the transmitter to the legitimate receiver while keeping the wire-tapper completely ignorant of the transmitted messages. Recently, there has been numerous studies addressing information theoretic security [2]-[5]. For instance, the impact of fading has been investigated in [2], where it has been shown that a non-zero secrecy capacity can be achieved even when the eavesdropper channel is better than the main channel on average. The secrecy capacity region of the fading broadcast channel with confidential messages and associated optimal power control policies have been identified in [3], where it is shown that the transmitter allocates more power as the strength of the main channel increases with respect to that of the eavesdropper channel.

In addition to security issues, providing acceptable performance and quality is vital to many applications. For instance, voice over IP (VoIP), interactive-video (e.g., videoconferencing), and streaming-video systems are required to satisfy certain buffer or delay constraints, and the recent proliferation and expected widespread use of multimedia applications in next generation wireless systems call for a rigorous performance analysis under such quality of service (QoS) considerations. A performance measure for these systems is the effective capacity [6], which can be seen as the maximum constant arrival rate that a given time-varying service process can support while satisfying statistical QoS constraints imposed in the form of limitations on the buffer length. Effective capacity is recently studied in various wireless scenarios (see e.g., [7]–[11] and references therein). For instance, Tang and Zhang in [7] considered the effective capacity when both the receiver and transmitter know the instantaneous channel gains, and derived the optimal power and rate adaptation policies that maximize the system throughput under QoS constraints. Liu *et al.* in [9] considered fixed-rate transmission schemes and analyzed the effective capacity and related resource requirements for Markov wireless channel models. In [10] and [11], energy efficiency is addressed when the wireless systems operate under buffer constraints and employ either adaptive or fixed transmission schemes.

The above-mentioned studies addressed the physical-layer security and QoS limitations separately. However, the joint treatment of these considerations is of much interest from both practical and theoretical points of view. The practical relevance is through, for instance, the wide range of military and commercial applications and scenarios in which sensitive multimedia information needs to be transmitted in a wireless and

secure fashion. The theoretical interest is due to the certain tension that arises when both secrecy and buffer limitations are present. For instance, physical layer security leads to lower transmission rates. Moreover, the optimal performance in wireless scenarios requires opportunistic transmissions in which one has to wait for high-rate transmission until the main channel between the transmitter and the legitimate receiver is much stronger than the eavesdropper's channel. Note that both end-results may cause buffer overflows and packet losses and may be detrimental in buffer/delay constrained systems. Despite these motivating facts, the combination of security and delay/buffer considerations has received only little attention so far. In [12], Liang *et al.* analyzed the arrival rates supported by a fading wire-tap channel and identified the power allocation policies that take into account the queue lengths. In [13], Youssef *et al.* studied the delay limited secrecy capacity of fading channels.

In this paper, we address both physical-layer security issues and buffer limitations in order to identify the key tradeoffs and optimal transmission strategies. We assume that perfect channel side information (CSI) is available at both the transmitter and receivers. We first consider a secure broadcasting scenario in which the transmitter sends common messages to two receivers and confidential messages to one receiver. For this case, we define the *effective secrecy throughput region* as the region of common and confidential message arrival rates that can be supported when the transmitter operates under constraints on buffer violation probabilities. Then, we investigate the optimal power allocation policies that achieve points on the boundary of the effective secrecy throughput region. We provide an algorithm to determine the power allocation as a function of the channel states. Subsequently, we provide a more detailed analysis of the special case in which the transmitter sends no common messages. In this case, the broadcast channel with confidential messages is reduced to a wiretap channel. In this scenario, we provide the expression for the effective secure throughput and analyze two types of control policies by adapting the power with respect to both the main and eavesdropper channel conditions and also with respect to only the main channel conditions. Through this analysis, we find that, due to the introduction of the buffer constraints, the transmitter cannot reserve its power for times at which the main channel is much stronger than the eavesdropper channel. Also, we find that adapting the power allocation strategy with respect to both the main and eavesdropper channel CSI rather than only the main channel CSI provides little improvement when QoS constraints become more stringent.

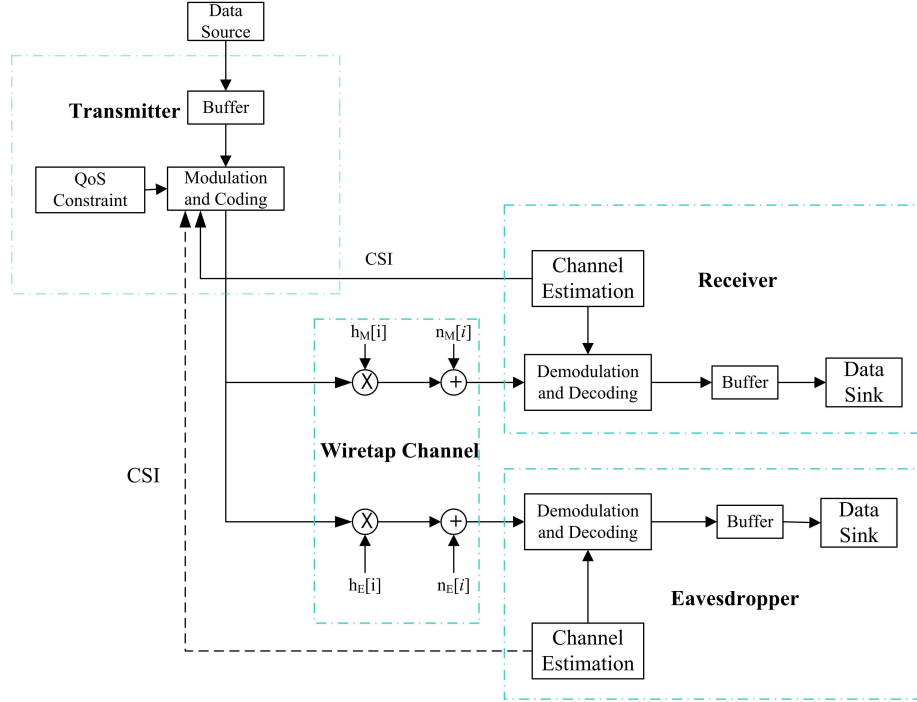


Fig. 1. The general system model.

The rest of the paper is organized as follows. Section II briefly describes the system model and the necessary preliminaries on statistical QoS constraints and effective capacity. In Section III, the effective secrecy throughput region and the corresponding optimal power allocation policies are presented for fading broadcast channels with confidential messages. In Section IV, the special case in which the common message rate is zero is studied in more detail. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND PRELIMINARIES

A. System and Channel Models

As depicted in Figure 1, we consider a system with one transmitter and two receivers. We assume that the transmitter sends confidential messages to receiver 1. From this perspective, receiver 2 can be regarded as an eavesdropper. However, receiver 2 is not necessarily a malicious eavesdropper as we also consider a broadcast scenario in which transmitter sends common messages to both receivers.

In the model, data sequences generated by the source are divided into frames of duration T . These data frames are initially stored in the buffer before they are transmitted over the wireless channel. The channel

input-output relationships are given by

$$Y_1[i] = h_1[i]X[i] + W_1[i] \quad (1)$$

and

$$Y_2[i] = h_2[i]X[i] + W_2[i] \quad (2)$$

where i is the symbol index, $X[i]$ is the channel input in the i th symbol duration, and $Y_1[i]$ and $Y_2[i]$ represent the channel outputs at receivers 1 and 2, respectively. We assume that $\{h_j[i], j = 1, 2\}$'s are jointly stationary and ergodic discrete-time processes, and we denote the magnitude-square of the fading coefficients by $z_j[i] = |h_j[i]|^2$. Considering the receiver 1 as the main user, to which we send both the common and confidential messages, and regarding receiver 2 as the eavesdropper for the confidential messages, we replace z_1 with z_M and z_2 with z_E to increase the clarity in the subsequent formulations. The channel input is subject to an average energy constraint $\mathbb{E}\{|X[i]|^2\} \leq \bar{P}/B$ where B is the bandwidth available in the system and hence \bar{P} is average power constraint (under the assumption that the symbol rate is B complex symbols per second). Above, $W_j[i]$ is a zero-mean, circularly symmetric, complex Gaussian random variable with variance $\mathbb{E}\{|W_j[i]|^2\} = N_j$. The additive Gaussian noise samples $\{W_j[i]\}$ are assumed to form an independent and identically distributed (i.i.d.) sequence.

We denote the average transmitted signal to noise ratio with respect to receiver 1 as $\text{SNR} = \frac{\bar{P}}{N_1 B}$. Also, we denote the instantaneous transmit power in the i th frame as $P[i]$. Now, the instantaneous transmitted SNR level for receiver 1 becomes $\mu^1[i] = \frac{P[i]}{N_1 B}$. Then, the average power constraint at the transmitter is equivalent to the average SNR constraint $\mathbb{E}\{\mu^1[i]\} \leq \text{SNR}$ for receiver 1 [15]. If we denote the ratio between the noise powers of the two channels as $\gamma = \frac{N_1}{N_2}$, the instantaneous transmitted SNR level for receiver 2 becomes $\mu^2[i] = \gamma\mu^1[i]$.

B. Secrecy Capacity Region with Common Messages

We consider a block-fading channel in which the fading coefficients stay constant for the block duration of T seconds and change independently across the blocks. We assume that both the transmitter and receivers have perfect channel side information (CSI). Equipped with the channel knowledge, the transmitter employs power control. We denote the power allocation policies for the common and confidential messages by $\mu = (\mu_0(\mathbf{z}), \mu_1(\mathbf{z}))$, respectively, where $\mathbf{z} = (z_M, z_E)$ is the vector composed of the channel states of receivers 1 and 2. Note that the power control policies are defined as instantaneous power levels normalized by the noise power N_1 at receiver 1, i.e., $\mu_0(\mathbf{z}) = \frac{P_0[i]}{N_1 B}$ and $\mu_1(\mathbf{z}) = \frac{P_1[i]}{N_1 B}$ where $P_0[i]$ and $P_1[i]$ are the instantaneous powers of the common and confidential messages as functions of the fading states \mathbf{z} . The region of fading states in which confidential messages are transmitted is $\mathcal{Z} = \{\mathbf{z} \geq 0 : z_M > \gamma z_E\}$ while the complement of this region in the first quadrant is $\mathcal{Z}^c = \{\mathbf{z} \geq 0 : z_M \leq \gamma z_E\}$. In \mathcal{Z}^c , eavesdropper's channel is stronger and instantaneous secrecy capacity is zero. Hence, when $\mathbf{z} \in \mathcal{Z}^c$, confidential messages are not transmitted and $\mu_1(\mathbf{z}) = 0$. Following the above definitions, we finally define \mathcal{U} as set of the power allocation policies that satisfy the average SNR constraint, i.e.,

$$\mathcal{U} = \left\{ \mu : \mathbb{E}_{\mathbf{z} \in \mathcal{Z}} \{\mu_0(\mathbf{z}) + \mu_1(\mathbf{z})\} + \mathbb{E}_{\mathbf{z} \in \mathcal{Z}^c} \{\mu_0(\mathbf{z})\} \leq \text{SNR} = \frac{\bar{P}}{N_1 B} \right\}. \quad (3)$$

With the above power control policies, the maximum instantaneous common message rate in each block with power control policy μ is given by [3, Section V]

$$R_0 = \begin{cases} \log_2(1 + \frac{\gamma \mu_0(\mathbf{z}) z_E}{1 + \gamma \mu_1(\mathbf{z}) z_E}), & \mathbf{z} \in \mathcal{Z} \\ \log_2(1 + \mu_0(\mathbf{z}) z_M), & \mathbf{z} \in \mathcal{Z}^c \end{cases} \quad (4)$$

under the assumption that channel coding is performed in each block of duration T seconds, and the block length, which is TB symbols, is large enough so that the probability of error is negligible and hence communication at these rates is reliable. Under similar assumptions, the maximum instantaneous confidential

message rate is given by

$$R_1 = \begin{cases} \log_2(1 + \mu_1(\mathbf{z})z_M) - \log_2(1 + \gamma\mu_1(\mathbf{z})z_E) & \mathbf{z} \in \mathcal{Z} \\ 0, & \mathbf{z} \in \mathcal{Z}^c \end{cases} \quad (5)$$

Then, the ergodic secrecy capacity region for the fading broadcast channel with common and confidential messages is¹

$$\mathcal{C}_s = \bigcup_{\mu \in \mathcal{U}} \left\{ \begin{array}{l} (R_{0,avg}, R_{1,avg}) : \\ R_{0,avg} \leq \mathbb{E}_{\mathbf{z} \in \mathcal{Z}} \left\{ \log_2 \left(1 + \frac{\gamma\mu_0(\mathbf{z})z_E}{1 + \gamma\mu_1(\mathbf{z})z_E} \right) \right\} + \mathbb{E}_{\mathbf{z} \in \mathcal{Z}^c} \{ \log_2(1 + \mu_0(\mathbf{z})z_M) \} \\ R_{1,avg} \leq \mathbb{E}_{\mathbf{z} \in \mathcal{Z}} \{ \log_2(1 + \mu_1(\mathbf{z})z_M) - \log_2(1 + \gamma\mu_1(\mathbf{z})z_E) \} \end{array} \right\}. \quad (6)$$

The following result shows the convexity of the above capacity region.

Proposition 1: The ergodic secrecy capacity region \mathcal{C}_s is convex.

Proof: Let $\mathbf{R} = (R_{0,avg}, R_{1,avg}) \in \mathcal{C}_s$ and $\mathbf{R}' = (R'_{0,avg}, R'_{1,avg}) \in \mathcal{C}_s$ be two rate pairs achieved by power control policies $\mu = (\mu_0(\mathbf{z}), \mu_1(\mathbf{z})) \in \mathcal{U}$ and $\mu' = (\mu'_0(\mathbf{z}), \mu'_1(\mathbf{z})) \in \mathcal{U}$, respectively. Now, assume that a time-sharing strategy is employed, and power control policy μ is used $\alpha \in (0, 1)$ fraction of the time and μ' is employed in the remaining $1 - \alpha$ fraction of the time. The new power control policy can be expressed as

$$\mu^* = \begin{cases} \mu, & \alpha \text{ fraction of the time} \\ \mu', & 1 - \alpha \text{ fraction of the time} \end{cases}. \quad (7)$$

Since $\mu \in \mathcal{U}$ and $\mu' \in \mathcal{U}$, we can easily see that $\mathbb{E}\{\mu^*\} = \alpha\mathbb{E}\{\mu\} + (1 - \alpha)\mathbb{E}\{\mu'\} \leq \text{SNR}$, and hence $\mu^* \in \mathcal{U}$ as well. Moreover, this time-sharing strategy achieves $\alpha\mathbf{R} + (1 - \alpha)\mathbf{R}'$ with the power control policy μ^* . Therefore, we conclude that $\mathbf{R} + (1 - \alpha)\mathbf{R}' \in \mathcal{C}_s$, showing the convexity of \mathcal{C}_s . \square

C. Statistical QoS Constraints and Effective Secure Throughput

In [6], effective capacity is defined as the maximum constant arrival rate² that a given service process can support in order to guarantee a statistical QoS requirement specified by the QoS exponent θ . If we define

¹Note that if coding over all channel states is allowed, a larger capacity region can be achieved (see e.g., [3, Section IV]).

²For time-varying arrival rates, effective capacity specifies the effective bandwidth of the arrival process that can be supported by the channel.

Q as the stationary queue length, then θ is the decay rate of the tail distribution of the queue length Q :

$$\lim_{q \rightarrow \infty} \frac{\log P(Q \geq q)}{q} = -\theta. \quad (8)$$

Therefore, for large q_{\max} , we have the following approximation for the buffer violation probability: $P(Q \geq q_{\max}) \approx e^{-\theta q_{\max}}$. Hence, while larger θ corresponds to more strict QoS constraints, smaller θ implies looser QoS guarantees. Similarly, if D denotes the steady-state delay experienced in the buffer, then $P(D \geq d_{\max}) \approx e^{-\theta \delta d_{\max}}$ for large d_{\max} , where δ is determined by the arrival and service processes [8].

The effective capacity is given by

$$C(\theta) = - \lim_{t \rightarrow \infty} \frac{1}{\theta t} \log_e \mathbb{E}\{e^{-\theta S[t]}\} \quad \text{bits/s}, \quad (9)$$

where the expectation is with respect to $S[t] = \sum_{i=1}^t s[i]$, which is the time-accumulated service process. $\{s[i], i = 1, 2, \dots\}$ denote the discrete-time stationary and ergodic stochastic service process. We define the effective capacity obtained when the service rate is confined by the secrecy capacity region as the *effective secure throughput*.

Under the block fading assumption, the service rate in the i th block is $s[i] = TBR$ bits per T seconds, where R is the instantaneous service rate for either common or confidential messages, and B is the bandwidth. Note that $s[i]$ varies independently from one block to another due to the block fading assumption. Then, (9) can be written as

$$C(\theta) = -\frac{1}{\theta T} \log_e \mathbb{E}_{\mathbf{z}}\{e^{-\theta TBR}\} \quad \text{bits/s}. \quad (10)$$

Above, if R is equal to R_0 in (4), then $C(\theta)$ is the maximum effective capacity (or equivalently the maximum constant arrival rate) of the common messages, which can be achieved with the power allocation policy $\mu = (\mu_0, \mu_1)$ under queueing constraints specified by the QoS exponent θ . Similarly, if $R = R_1$ in (5), then $C(\theta)$ is the maximum effective capacity of the confidential messages achieved with the power control policy μ . Note that in both cases, R depends on the fading states \mathbf{z} , and the expectation in (10) is with respect to \mathbf{z} .

Finally, we denote the effective capacity normalized by bandwidth B as

$$C(\theta) = \frac{C(\theta)}{B} \quad \text{bits/s/Hz.} \quad (11)$$

III. EFFECTIVE SECURE THROUGHPUT REGION WITH COMMON MESSAGES AND OPTIMAL POWER CONTROL

In this section, we investigate the secure throughput region of and the optimal power control policies for the fading broadcast channel with confidential messages (BCC) in the presence of statistical QoS constraints. Hence, in the considered scenario, the transmitter sends common messages to two receivers, sends confidential messages to only one receiver, and operates under buffer constraints. Liang *et al.* in [3] showed that the fading channel can be viewed as a set of parallel subchannels with each subchannel corresponding to one fading state. Subsequently, the ergodic secrecy capacity region is determined and the optimal power allocation policies achieving the boundary of the capacity region are identified in [3]. Outage performance is also studied for cases in which long transmission delays cannot be tolerated and coding and decoding needs to be performed in one block.

A. Effective Secure Throughput Region

In this paper, we analyze the performance under statistical buffer constraints by considering the effective capacity formulation. Using the effective capacity expression in (10), we first have the following definition for the effective throughput region.

Definition 1: The effective secure throughput region of the fading BCC is

$$\mathcal{C}_{es} = \bigcup_{\substack{\mathbf{R}=(R_0, R_1) \\ \text{s.t. } \mathbb{E}\{\mathbf{R}\} \in \mathcal{C}_s}} \left\{ (C_0, C_1) : C_j \leq -\frac{1}{\theta T B} \log_e \mathbb{E}\{e^{-\theta T B R_j}\} \right\} \quad (12)$$

where $\mathbf{R} = (R_0, R_1)$ is the vector composed of the instantaneous rates for the common and confidential messages, respectively.

Note that the union in (12) is over the distributions of the vector \mathbf{R} such that the expected value $\mathbb{E}\{\mathbf{R}\}$ lies in the ergodic secrecy capacity region \mathcal{C}_s . Note also that the maximum values of the instantaneous rates

R_0 and R_1 for a given power control policy μ are provided by (4) and (5). Moreover, in (12), C_0 and C_1 denote the effective capacities of common and confidential messages, respectively.

Since the ergodic secrecy capacity region is convex as proved in Proposition 1, we can easily prove the following.

Theorem 1: The effective secrecy throughput region \mathcal{C}_{es} defined in (12) is convex.

Proof: Let the two effective capacity pairs $\underline{C} = (C_0, C_1)$ and $\underline{C}' = (C'_0, C'_1)$ belong to \mathcal{C}_{es} . Therefore, there exist some $\mathbf{R} = (R_0, R_1)$ and $\mathbf{R}' = (R'_0, R'_1)$ for \underline{C} and \underline{C}' , respectively. By a time sharing strategy, for any $\alpha \in (0, 1)$, we know that $\mathbb{E}\{\alpha\mathbf{R} + (1 - \alpha)\mathbf{R}'\} \in \mathcal{C}_s$. Then, we can write

$$\begin{aligned} & \alpha\underline{C} + (1 - \alpha)\underline{C}' \\ &= -\frac{1}{\theta TB} \log_e \left(\mathbb{E} \left\{ e^{-\theta TB \mathbf{R}} \right\} \right)^\alpha \left(\mathbb{E} \left\{ e^{-\theta TB \mathbf{R}'} \right\} \right)^{1-\alpha} \end{aligned} \quad (13)$$

$$= -\frac{1}{\theta TB} \log_e \left(\mathbb{E} \left\{ \left(e^{-\theta TB \alpha \mathbf{R}} \right)^{\frac{1}{\alpha}} \right\} \right)^\alpha \left(\mathbb{E} \left\{ \left(e^{-\theta TB (1-\alpha) \mathbf{R}'} \right)^{\frac{1}{1-\alpha}} \right\} \right)^{1-\alpha} \quad (14)$$

$$\leq -\frac{1}{\theta TB} \log_e \mathbb{E} \left\{ e^{-\theta TB (\alpha \mathbf{R} + (1-\alpha) \mathbf{R}')} \right\}. \quad (15)$$

Above, in (13) – (15), all algebraic operations are with respect to each component of the vectors. For instance, the expression in (13) denotes a vector whose components are $\left\{ \frac{1}{\theta TB} \log_e \left(\mathbb{E} \left\{ e^{-\theta TB R_j} \right\} \right)^\alpha \left(\mathbb{E} \left\{ e^{-\theta TB R'_j} \right\} \right)^{1-\alpha} \right\}$ for $j = 0, 1$. The inequality in (15) follows from Hölder's inequality. Hence, $\alpha\underline{C} + (1 - \alpha)\underline{C}'$ lies in the *throughput region*, showing the convexity. \square

Due to the convexity property, the points on the boundary surface of the effective throughput region (C_0^*, C_1^*) can be obtained by solving the following optimization problem

$$\max_{\mu \in \mathcal{U}} \lambda_0 C_0 + \lambda_1 C_1 \quad (16)$$

where $\lambda = (\lambda_0, \lambda_1)$ is any vector in \mathfrak{R}_+^2 , and C_0 and C_1 are the maximum effective capacity values for a given power control policy μ , i.e., they are the effective capacity values when the instantaneous service rates are the ones given in (4) and (5).

B. Optimal Power Control

Having characterized the effective secure throughput region, we turn our attention to optimal power control. Note that due to the introduction of QoS constraints, the maximization is over the effective capacities while the service rates are limited by the instantaneous channel capacities.

Next, we derive the optimality conditions for the optimal power allocation μ^* that solves (16). As also provided in Section II-B, the maximal instantaneous common message rate for a given power control policy μ is

$$R_0 = \begin{cases} \log_2 \left(1 + \frac{\gamma \mu_0(\mathbf{z}) z_E}{1 + \gamma \mu_1(\mathbf{z}) z_E} \right), & \mathbf{z} \in \mathcal{Z} \\ \log_2 (1 + \mu_0(\mathbf{z}) z_M), & \mathbf{z} \in \mathcal{Z}^c \end{cases}. \quad (17)$$

Similarly, the maximal instantaneous confidential message (or equivalently secrecy) rate is

$$R_1 = \begin{cases} \log_2 \left(\frac{1 + \mu_1(\mathbf{z}) z_M}{1 + \gamma \mu_1(\mathbf{z}) z_E} \right), & \mathbf{z} \in \mathcal{Z} \\ 0, & \mathbf{z} \in \mathcal{Z}^c \end{cases}. \quad (18)$$

Now, using these instantaneous service rates R_0 and R_1 in the effective capacity expressions and recalling the average SNR constraint in (3), we can express the Lagrangian of the convex optimization problem in (16) as

$$\begin{aligned} \mathcal{J} = & -\frac{\lambda_0}{\beta \log_e 2} \log_e \left(\int_{\mathbf{z} \in \mathcal{Z}} \left(1 + \frac{\gamma \mu_0(\mathbf{z}) z_E}{1 + \gamma \mu_1(\mathbf{z}) z_E} \right)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} + \int_{\mathbf{z} \in \mathcal{Z}^c} (1 + \mu_0(\mathbf{z}) z_M)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} \right) \\ & -\frac{\lambda_1}{\beta \log_e 2} \log_e \left(\int_{\mathbf{z} \in \mathcal{Z}} \left(\frac{1 + \mu_1(\mathbf{z}) z_M}{1 + \gamma \mu_1(\mathbf{z}) z_E} \right)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} + \int_{\mathbf{z} \in \mathcal{Z}^c} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} \right) \\ & -\kappa (\mathbb{E}_{\mathbf{z} \in \mathcal{Z}} \{\mu_0(\mathbf{z}) + \mu_1(\mathbf{z})\} + \mathbb{E}_{\mathbf{z} \in \mathcal{Z}^c} \{\mu_0(\mathbf{z})\}) \end{aligned} \quad (19)$$

where $\beta = \frac{\theta TB}{\log_e 2}$, $p_{\mathbf{z}}(z_M, z_E)$ is the joint distribution function of the fading states $\mathbf{z} = (z_M, z_E)$, and $\kappa \geq 0$ is the Lagrange multiplier. Next, we define (ϕ_0, ϕ_1) as

$$\phi_0 = \int_{\mathbf{z} \in \mathcal{Z}} \left(1 + \frac{\gamma \mu_0(\mathbf{z}) z_E}{1 + \gamma \mu_1(\mathbf{z}) z_E} \right)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} + \int_{\mathbf{z} \in \mathcal{Z}^c} (1 + \mu_0(\mathbf{z}) z_M)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z}, \quad (20)$$

and

$$\phi_1 = \int_{\mathbf{z} \in \mathcal{Z}} \left(\frac{1 + \mu_1(\mathbf{z})z_M}{1 + \gamma\mu_1(\mathbf{z})z_E} \right)^{-\beta} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z} + \int_{\mathbf{z} \in \mathcal{Z}^c} p_{\mathbf{z}}(z_M, z_E) d\mathbf{z}. \quad (21)$$

Below, we derive the optimality conditions (that the optimal power control policies should satisfy) by differentiating the Lagrangian with respect to μ_0 in regions \mathcal{Z}^c and \mathcal{Z} and with respect to μ_1 in \mathcal{Z} , and making the derivatives equal to zero:

$$1) \frac{\lambda_0}{\phi_0 \log_e 2} (1 + \mu_0 z_M)^{-\beta-1} z_M - \kappa = 0 \quad \forall \mathbf{z} \in \mathcal{Z}^c \quad (22)$$

$$2) \frac{\lambda_0}{\phi_0 \log_e 2} \left(1 + \frac{\gamma\mu_0 z_E}{1 + \gamma\mu_1 z_E} \right)^{-\beta-1} \frac{\gamma z_E}{1 + \gamma\mu_1 z_E} - \kappa = 0 \quad \forall \mathbf{z} \in \mathcal{Z} \quad (23)$$

$$3) -\frac{\lambda_0}{\phi_0 \log_e 2} \left(1 + \frac{\gamma\mu_0 z_E}{1 + \gamma\mu_1 z_E} \right)^{-\beta-1} \frac{\mu_0 (\gamma z_E)^2}{(1 + \gamma\mu_1 z_E)^2} + \frac{\lambda_1}{\phi_1 \log_e 2} \left(\frac{1 + \mu_1 z_M}{1 + \gamma\mu_1 z_E} \right)^{-\beta-1} \frac{z_M - \gamma z_E}{(1 + \gamma\mu_1 z_E)^2} - \kappa = 0 \quad \forall \mathbf{z} \in \mathcal{Z} \quad (24)$$

where (22)-(24) are obtained by evaluating the derivative of \mathcal{J} with respect to μ_0 when $\mathbf{z} \in \mathcal{Z}^c$, μ_0 when $\mathbf{z} \in \mathcal{Z}$, and μ_1 when $\mathbf{z} \in \mathcal{Z}$, respectively. Whenever μ_0 or μ_1 turns out to have negative values through these equations, they are set to 0.

We immediately note from (22) that when $\mathbf{z} \in \mathcal{Z}^c$ (i.e., when $z_M \leq \gamma z_E$ and no confidential messages are transmitted), the optimal power control policy for the common messages can be expressed as

$$\mu_0 = \left[\frac{1}{\alpha_1^{\frac{1}{\beta+1}} z_M^{\frac{\beta}{\beta+1}}} - \frac{1}{z_M} \right]^+ \quad \forall \mathbf{z} \in \mathcal{Z}^c \quad (25)$$

where $\alpha_1 = \frac{\kappa \phi_0 \log_e 2}{\lambda_0}$. Also, when $\mathbf{z} \in \mathcal{Z}$, if no power is allocated for confidential messages and hence $\mu_1 = 0$, then we see from (23) that we can write the optimal μ_0 as

$$\mu_0 = \left[\frac{1}{\alpha_1^{\frac{1}{\beta+1}} (\gamma z_E)^{\frac{\beta}{\beta+1}}} - \frac{1}{\gamma z_E} \right]^+ \quad \forall \mathbf{z} \in \mathcal{Z}. \quad (26)$$

A final remark about μ_0 is the following. Noting that the term $\left(1 + \frac{\gamma\mu_0 z_E}{1 + \gamma\mu_1 z_E} \right)^{-\beta-1}$ in (23) is less than 1 for $\mu_0 > 0$, we have $\frac{\lambda_0}{\phi_0 \log_e 2} \frac{\gamma z_E}{1 + \gamma\mu_1 z_E} > \kappa$ when $\mu_0 > 0$. Equivalently, having $\frac{\lambda_0}{\phi_0 \log_e 2} \frac{\gamma z_E}{1 + \gamma\mu_1 z_E} \leq \kappa$ implies that

$\mu_0 = 0$.

Regarding the optimal power control for the confidential messages, we have the following observations from the optimality conditions. We remark that when $\mu_0 = 0$, (24) becomes

$$\frac{\lambda_1}{\phi_1 \log_e 2} \left(\frac{1 + \mu_1 z_M}{1 + \gamma \mu_1 z_E} \right)^{-\beta-1} \frac{z_M - \gamma z_E}{(1 + \gamma \mu_1 z_E)^2} - \kappa = 0 \quad (27)$$

from which the optimal μ_1 can be computed.

When we have both $\mu_0 > 0$ and $\mu_1 > 0$, the optimal power allocations can be obtained by solving (23) and (24) simultaneously. In this case, a certain condition that depends only on μ_1 can be obtained. By combining the equations in (23) and (24) and applying several straightforward algebraic manipulations, we get

$$\frac{\lambda_1}{\kappa \phi_1 \log_e 2} \left(\frac{1 + \mu_1 z_M}{1 + \gamma \mu_1 z_E} \right)^{-\beta-1} \frac{z_M - \gamma z_E}{(1 + \gamma \mu_1 z_E)^2} - \left(\frac{\lambda_0}{\kappa \phi_0 \log_e 2} \frac{\gamma z_E}{1 + \gamma \mu_1 z_E} \right)^{\frac{1}{\beta+1}} = 0 \quad (28)$$

which depends only on μ_1 . The positive solution $\mu_1 > 0$ of this equation provides the optimal power control policy for the confidential messages. Once optimal μ_1 is determined, the optimal policy μ_0 can be easily found from (23).

As seen in the above discussion, we have closed-form expressions for the optimal power control policy for the common messages in special cases (e.g., when $\mathbf{z} \in \mathcal{Z}^c$ or when $\mu_1 = 0$). On the other hand, the optimal power control policy for the confidential messages does not assume simple closed-form formulas even in special cases. Hence, optimal power control is in general determined through numerical computations. Making use of the optimality conditions in (22) – (24) and the characterizations in (25) through (28), we propose the following algorithm to obtain the optimal power adaptation policies. This algorithm is used in the numerical results presented in Section III-C.

ALGORITHM PC (*Power Control*)

```

1  Given  $\lambda_0, \lambda_1$ , initialize  $\phi_0, \phi_1$ ;
2  Initialize  $\kappa$ ;
3  Determine  $\alpha_1 = \frac{\kappa\phi_0 \log_e 2}{\lambda_0}$ ,  $\alpha_2 = \frac{\kappa\phi_1 \log_e 2}{\lambda_1}$ ;
4  if  $z_M - \gamma z_E > 0$ 
5      then if  $z_M - \gamma z_E > \alpha_2$ 
6          then Compute  $\mu_1$  from (27);
7              if  $\mu_1 > \frac{1}{\alpha_1} - \frac{1}{\gamma z_E}$  or  $\gamma z_E < \alpha_1$ 
8                  then  $\mu_0 = 0$ ;
9                  else if (28) returns positive solution
10                     then Compute  $\mu_0$  and  $\mu_1$  from (23) and (24);
11                     else  $\mu_1 = 0$ ,  $\mu_0 = \left[ \frac{1}{\alpha_1^{\frac{1}{\beta+1}} (\gamma z_E)^{\frac{\beta}{\beta+1}}} - \frac{1}{\gamma z_E} \right]^+$ ;
12                     else  $\mu_1 = 0$ ,  $\mu_0 = \left[ \frac{1}{\alpha_1^{\frac{1}{\beta+1}} (\gamma z_E)^{\frac{\beta}{\beta+1}}} - \frac{1}{\gamma z_E} \right]^+$ ;
13                     else  $\mu_1 = 0$ ,  $\mu_0 = \left[ \frac{1}{\alpha_1^{\frac{1}{\beta+1}} z_M^{\frac{\beta}{\beta+1}}} - \frac{1}{z_M} \right]^+$ ;
14  Check if the obtained  $\mu_0$  and  $\mu_1$  satisfy the average power constraint with equality;
15  if not satisfied with equality
16      then update the value of  $\kappa$  and return to Step 3;
17      else move to Step 18;
18  Evaluate  $\phi_0$  and  $\phi_1$  with the obtained power control policies;
19  Check if the new values of  $\phi_0$  and  $\phi_1$  agree (up to a certain margin) with those used in Step 3;
20  if do not agree
21      then update the values of  $\phi_0$  and  $\phi_1$  and return to Step 2;
22      else declare the obtained power allocation policies  $\mu_1$  and  $\mu_2$  as the optimal ones.

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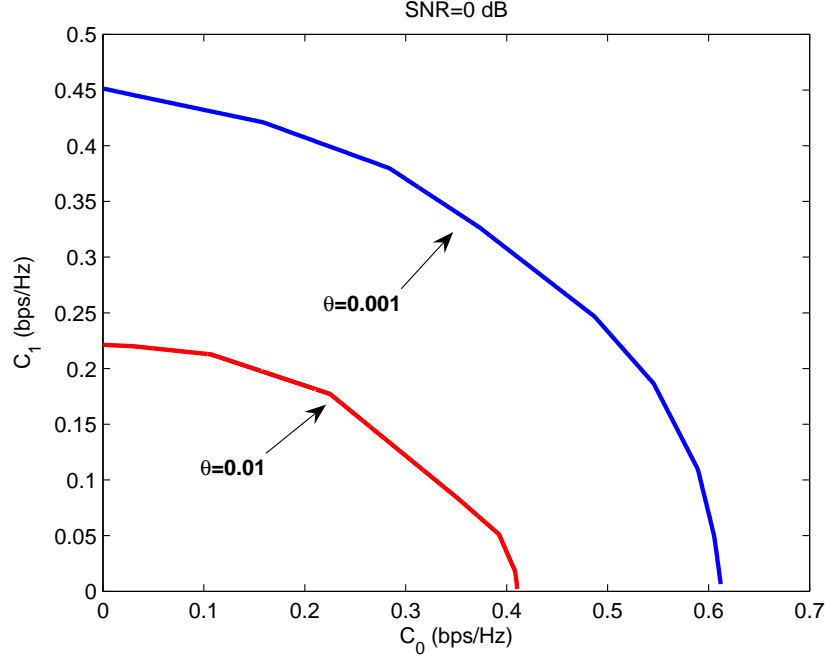


Fig. 2. The effective secrecy throughput region for $\theta = 0.01$ and $\theta = 0.001$.

C. Numerical Results

In Fig. 2, we plot the effective secrecy throughput region for different θ values in a Rayleigh fading environment in which z_M and z_E are independent exponential random variables with $\mathbb{E}\{z_M\} = \mathbb{E}\{z_E\} = 1$. We assume that $\gamma = 1$, i.e., the noise variances at both receivers are equal. We further assume that $\text{SNR} = 0$ dB. In the figure, we can observe that as θ increases and hence QoS constraints becomes more stringent, the effective throughput region shrinks. It is interesting to note that the percentage-wise decrease in the boundary point on the y -axis (i.e., the maximum effective secrecy capacity C_1 when common message rate is zero) is more than that in the boundary point on the x -axis (i.e., the maximum effective capacity C_0 when confidential message rate is zero). Hence, we see that the secrecy effective capacity is more severely affected by more strict QoS limitations.

We know that as SNR decreases, the maximal instantaneous service rate for common/confidential messages decreases as well. In Fig. 3, we plot the effective secrecy throughput region for different SNR values. We assume that $\theta = 0.01$. As we see from the figure, smaller SNR introduces significant reduction in the

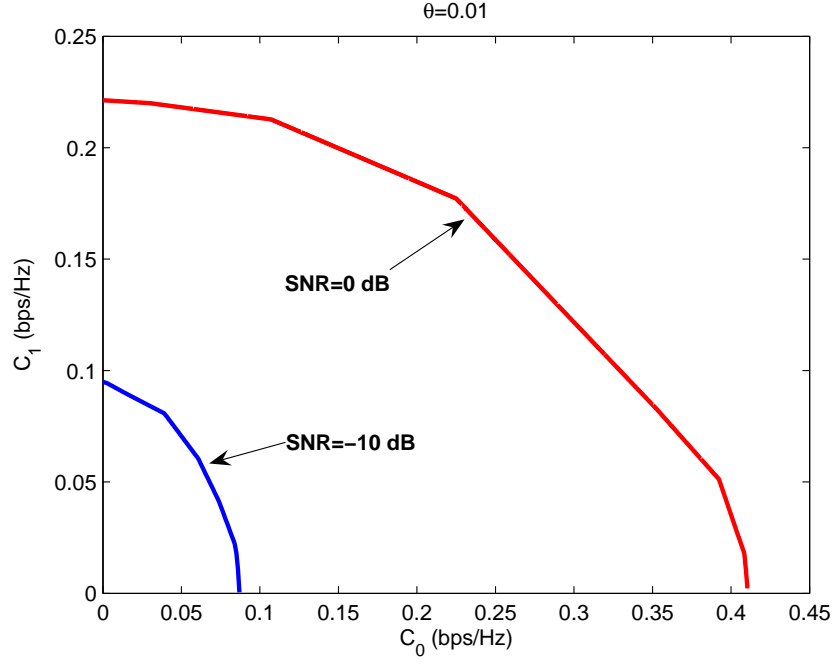


Fig. 3. The effective secrecy throughput region for SNR = 0 dB and SNR = -10 dB. $\theta = 0.01$.

effective throughput region. Moreover, it is interesting to note that, contrary to the observation we had in Fig. 2, the decrease in the boundary point C_1 when $C_0 = 0$ is relatively smaller compared to the decrease in the boundary point C_0 when $C_1 = 0$. Hence, a more severe impact is experienced by the common message rates.

Finally, we plot the optimal power adaptation policies $\mu_0(\mathbf{z})$ and $\mu_1(\mathbf{z})$ as a function of the channel states $\mathbf{z} = (z_M, z_E)$ in Fig. 4. In the figure, we have SNR = -10 dB and $\theta = 0.01$. Moreover, we assume $\lambda_0 = 0.5$, and hence these are the optimal power control policies that maximize the sum rate throughput $C_0 + C_1$. It is obvious from the figure that the power for common message seems to be relatively uniformly distributed over all the entire channel state space while the power for confidential messages is concentrated in the smaller region \mathcal{Z} . Still, we note that the optimal μ_1 provides relatively uniform distribution in \mathcal{Z} rather than an opportunistic power allocation strategy in which more power is allocated to the transmission of confidential messages when z_M is much larger than z_E and less power otherwise. As will also be seen in the discussions of the following section, opportunistic power control is not necessarily optimal in the presence

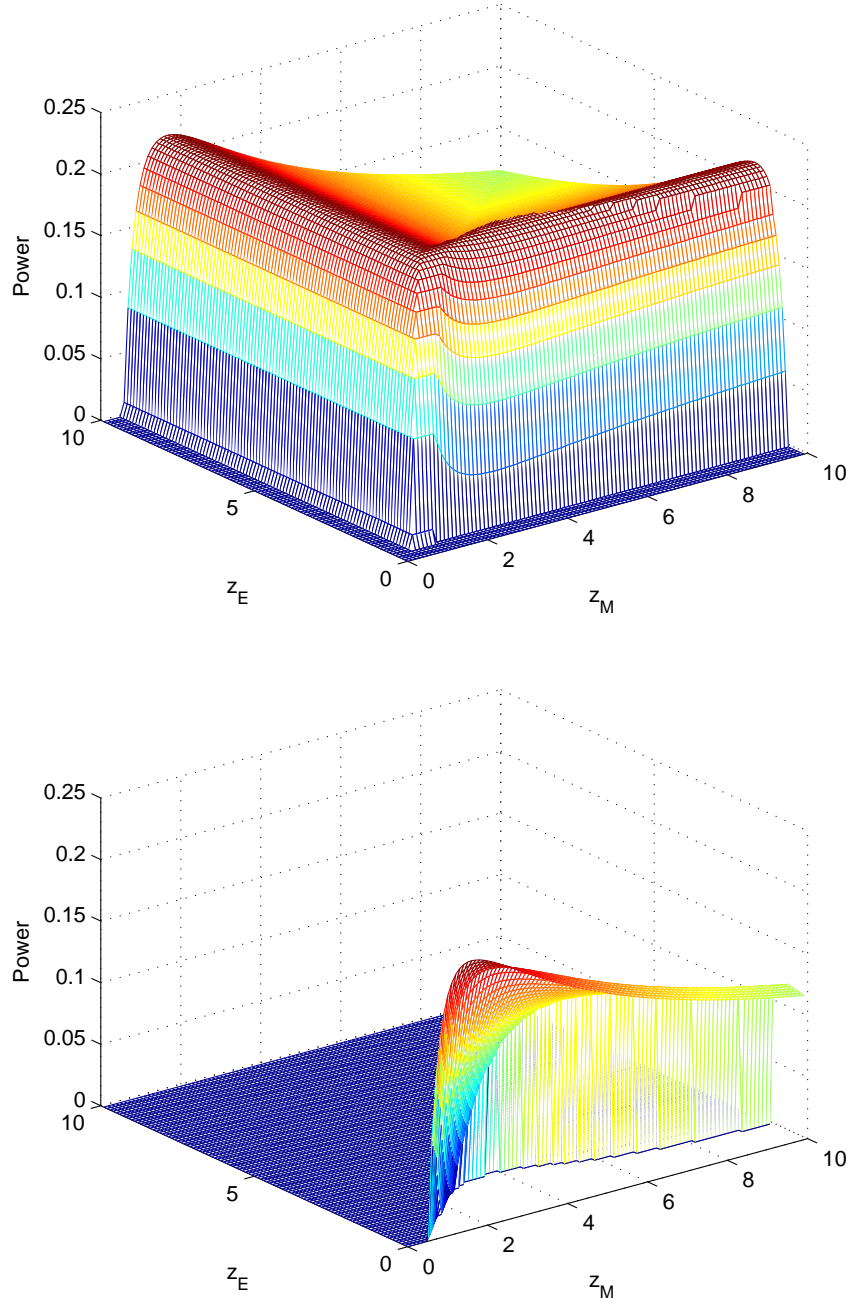


Fig. 4. The power allocated to common message and confidential message transmissions as a function of $\mathbf{z} = (z_M, z_E)$. The top figure plots the power control policy μ_0 , while the figure below plots the power control policy μ_1 . $\lambda_0 = 0.5$. $\text{SNR} = -10$ dB. $\theta = 0.01$.

of buffer constraints as waiting until channel conditions gets favorable may lead to buffer overflows.

IV. EFFECTIVE SECURE THROUGHPUT AND OPTIMAL POWER CONTROL IN THE ABSENCE OF COMMON MESSAGES

In this section, we assume that the common message rate is zero, i.e., $R_0 = 0$, and investigate the secrecy capacity and the associated optimal power control policy in the presence of QoS constraints. For this case, we identify equivalent optimization problems that are simpler to solve than the ones studied in Section III. In particular, we analyze two types of power adaptation policies. First, we consider the case in which the power control policies take into account the CSI of both the main and eavesdropper channels. Subsequently, we investigate power allocation strategies that are functions of only the CSI of the main channel.

A. Power Adaptation with Main and Eavesdropper Channel State Information

In this subsection, we assume that transmitter adapts the transmitted power according to the instantaneous values of z_M and z_E . Recall that the instantaneous secrecy rate with power adaptation policy $\mu(z_M, z_E)$ is given by

$$R_1 = \begin{cases} \log_2(1 + \mu(z_M, z_E)z_M) - \log_2(1 + \gamma\mu(z_M, z_E)z_E), & \mathbf{z} \in \mathcal{Z} \\ 0, & \mathbf{z} \in \mathcal{Z}^c \end{cases} \quad (29)$$

and the maximum effective secure throughput can be expressed as

$$\begin{aligned} C_1 = & \max_{\substack{\mu(z_M, z_E) \\ \mathbb{E}\{\mu(z_M, z_E)\} \leq \text{SNR}}} -\frac{1}{\theta TB} \log_e \left(\int_0^\infty \int_0^{\gamma z_E} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E \right. \\ & \left. + \int_0^\infty \int_{\gamma z_E}^\infty \left(\frac{1 + \mu(z_M, z_E)z_M}{1 + \gamma\mu(z_M, z_E)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E \right) \end{aligned} \quad (30)$$

where $p_{z_M}(z_M)$ and $p_{z_E}(z_E)$ are the probability density functions of z_M and z_E , respectively³, and $\beta = \frac{\theta TB}{\log_e 2}$. Note that the first term in the log function is a constant and log is a monotonically increasing function.

³In Section IV, we assume that z_M and z_E are independent. While this is not necessarily required in Section IV-A, optimal control policy results in Section IV-B depend on this assumption. Hence, we have the same assumption throughout Section IV for the sake of being consistent.

Therefore, the maximization problem in (30) is equivalent to the following minimization problem

$$\min_{\substack{\mu(z_M, z_E) \\ \mathbb{E}\{\mu(z_M, z_E)\} \leq \text{SNR}}} \int_0^\infty \int_{\gamma z_E}^\infty \left(\frac{1 + \mu(z_M, z_E)z_M}{1 + \gamma\mu(z_M, z_E)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E. \quad (31)$$

It is easy to check that when $z_M > \gamma z_E$,

$$f(\mu) = \left(\frac{1 + \mu z_M}{1 + \gamma\mu z_E} \right)^{-\beta} \quad (32)$$

is a convex function in μ . Since nonnegative weighted sum of convex functions is convex [16], we can immediately see that the objective function in (31) is also convex in μ . Then, we can form the following Lagrangian function, denoted as \mathcal{J} :

$$\begin{aligned} \mathcal{J} = & \int_0^\infty \int_{\gamma z_E}^\infty \left(\frac{1 + \mu(z_M, z_E)z_M}{1 + \gamma\mu(z_M, z_E)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E \\ & + \lambda \left(\int_0^\infty \int_{\gamma z_E}^\infty \mu(z_M, z_E) p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E - \text{SNR} \right). \end{aligned} \quad (33)$$

Taking the derivative of the Lagrangian function with respect to $\mu(z_M, z_E)$, we get the following optimality condition:

$$\frac{\partial \mathcal{J}}{\partial \mu(z_M, z_E)} = \lambda - \beta \left(\frac{1 + \mu(z_M, z_E)z_M}{1 + \gamma\mu(z_M, z_E)z_E} \right)^{-\beta} \frac{z_M - \gamma z_E}{(1 + \mu(z_M, z_E)z_M)(1 + \gamma\mu(z_M, z_E)z_E)} = 0 \quad (34)$$

where λ is the Lagrange multiplier whose value is chosen to satisfy the average power constraint with equality. For any channel state pairs (z_M, z_E) , $\mu(z_M, z_E)$ can be obtained from the above condition. Whenever the value of $\mu(z_M, z_E)$ is negative, it follows from the convexity of the objective function with respect to $\mu(z_M, z_E)$ that the optimal value of $\mu(z_M, z_E)$ is 0.

There is no closed-form solution to (34). However, since the right-hand side (RHS) of (34) is a monotonically increasing function, numerical techniques such as bisection search method can be efficiently adopted to derive the solution.

The secure throughput can be determined by substituting the optimal power control policy $\mu^*(z_M, z_E)$ in (30). Exploiting the optimality condition in (34), we can notice that when $\mu(z_M, z_E) = 0$, we have

$z_M - \gamma z_E = \frac{\lambda}{\beta}$. Meanwhile,

$$\left(\frac{1 + \mu(z_M, z_E)z_M}{1 + \gamma\mu(z_M, z_E)z_E} \right)^{-\beta} \frac{1}{(1 + \mu(z_M, z_E)z_M)(1 + \gamma\mu(z_M, z_E)z_E)} < 1. \quad (35)$$

Thus, we must have $z_M - \gamma z_E > \frac{\lambda}{\beta}$ for $\mu(z_M, z_E) > 0$, i.e., $\mu(z_M, z_E) = 0$ if $z_M - \gamma z_E \leq \frac{\lambda}{\beta}$. Hence, we can write the maximum effective secure throughput as

$$\begin{aligned} C_1 = & -\frac{1}{\theta TB} \log_e \left(\int_0^\infty \int_0^{\gamma z_E + \frac{\lambda}{\beta}} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E \right. \\ & \left. + \int_0^\infty \int_{\gamma z_E + \frac{\lambda}{\beta}}^\infty \left(\frac{1 + \mu^*(z_M, z_E)z_M}{1 + \gamma\mu^*(z_M, z_E)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_M dz_E \right) \end{aligned} \quad (36)$$

where $\mu^*(\theta, z_M, z_E)$ is the derived optimal power control policy.

B. Power Adaptation with only Main Channel State Information

In this section, we assume that the transmitter adapts the power level by only taking into account the CSI of the main channel (the channel between the transmitter and the legitimate receiver). Under this assumption, the instantaneous secrecy rate with power adaptation policy $\mu(z_M)$ is

$$R_1 = \begin{cases} \log_2(1 + \mu(z_M)z_M) - \log_2(1 + \gamma\mu(z_M)z_E), & \mathbf{z} \in \mathcal{Z} \\ 0, & \mathbf{z} \in \mathcal{Z}^c \end{cases} \quad (37)$$

and the maximum effective secure throughput is

$$\begin{aligned} C_1 = & \max_{\substack{\mu(z_M) \\ \mathbb{E}\{\mu(z_M)\} \leq \text{SNR}}} -\frac{1}{\theta TB} \log_e \left(\int_0^\infty \int_{z_M/\gamma}^\infty p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M \right. \\ & \left. + \int_0^\infty \int_0^{z_M/\gamma} \left(\frac{1 + \mu(z_M)z_M}{1 + \gamma\mu(z_M)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M \right). \end{aligned} \quad (38)$$

Similar to the discussion in Section IV-A, we get the following equivalent minimization problem:

$$\min_{\substack{\mu(z_M) \\ \mathbb{E}\{\mu(z_M)\} \leq \text{SNR}}} \int_0^\infty \int_0^{z_M/\gamma} \left(\frac{1 + \mu(z_M)z_M}{1 + \gamma\mu(z_M)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M. \quad (39)$$

The objective function in this case is again convex, and with a similar Lagrangian optimization method, we can get the following optimality condition:

$$\frac{\partial \mathcal{J}}{\partial \mu(z_M)} = -\beta \int_0^{z_M/\gamma} \left(\frac{1 + \mu(z_M)z_M}{1 + \gamma\mu(z_M)z_E} \right)^{-\beta-1} \frac{z_M - \gamma z_E}{(1 + \gamma\mu(z_M)z_E)^2} p_{z_E}(z_E) dz_E + \lambda = 0 \quad (40)$$

where λ is the Lagrange multiplier whose value is chosen to satisfy the average power constraint with equality. If the obtained power level $\mu(z_M)$ is negative, then the optimal value of $\mu(z_M)$ becomes 0 according to the convexity of the objective function in (39). The RHS of (40) is still a monotonic increasing function of $\mu(z_M)$.

The secure throughput can be determined by substituting the optimal power control policy $\mu^*(z_M)$ in (38). Exploiting the optimality condition in (40), we can notice that when $\mu(z_M, z_E) = 0$, we have

$$-\beta \int_0^{z_M/\gamma} (z_M - \gamma z_E) p_{z_E}(z_E) dz_E + \lambda = 0 \quad (41)$$

$$\Rightarrow \int_0^{z_M} P(z_E \leq t/\gamma) dt = \frac{\lambda}{\beta} \quad (42)$$

Let us denote the solution to the above equation as α . Considering that

$$\left(\frac{1 + \mu(z_M)z_M}{1 + \gamma\mu(z_M)z_E} \right)^{-\beta-1} \frac{1}{(1 + \gamma\mu(z_M)z_E)^2} < 1, \quad (43)$$

we must have $z_M > \alpha$ for $\mu(z_M) > 0$, i.e., $\mu(z_M) = 0$ if $z_M \leq \alpha$. Hence, we can write the maximum effective secure throughput as

$$\begin{aligned} C_1 = & -\frac{1}{\theta T B} \log_e \left(\int_0^\alpha \int_0^\infty p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M + \int_\alpha^\infty \int_{z_M/\gamma}^\infty p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M \right. \\ & \left. + \int_\alpha^\infty \int_0^{z_M/\gamma} \left(\frac{1 + \mu^*(z_M)z_M}{1 + \gamma\mu^*(z_M)z_E} \right)^{-\beta} p_{z_M}(z_M) p_{z_E}(z_E) dz_E dz_M \right) \end{aligned} \quad (44)$$

where $\mu^*(z_M)$ is the derived optimal power control policy.

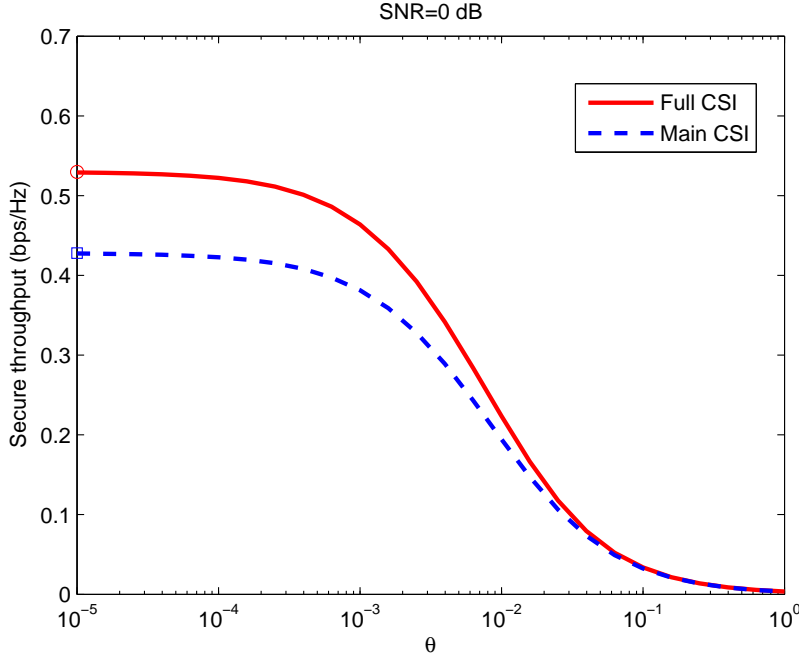


Fig. 5. The effective secure throughput vs. θ in the Rayleigh fading channel with $\mathbb{E}\{z_E\} = \mathbb{E}\{z_M\} = 1$. $\gamma = 1$.

C. Numerical Results

In Fig. 5, we plot the effective secure throughput as a function of the QoS exponent θ in Rayleigh fading channel with $\gamma = 1$ when the power is adapted with respect to the full CSI (i.e., the CSI of main and eavesdropper channels) and also with respect to only the main CSI. It can be seen from the figure that as the QoS constraints become more stringent and hence as the value of θ increases, little improvement is provided by considering the CSI of the eavesdropper channel in the power adaptation. In Fig. 6, we plot the effective secure throughput as SNR varies for $\theta = \{0, 0.001, 0.01, 0.1\}$. Not surprisingly, we again observe that taking into account the CSI of the eavesdropper channel in the power adaptation policy does not provide much gains in terms of increasing the effective secure throughput in the large SNR regime. Also, as QoS constraints become more strict, we similarly note that adapting the power with full CSI does not increase the rate of secure transmission much even at medium SNR levels.

To characterize the power allocation strategy, we plot in Fig. 7 the power distribution as a function of (z_M, z_E) for the full CSI case when $\theta = 0.01$ and $\theta = 0$. In the figure, we see that for both values of θ , no

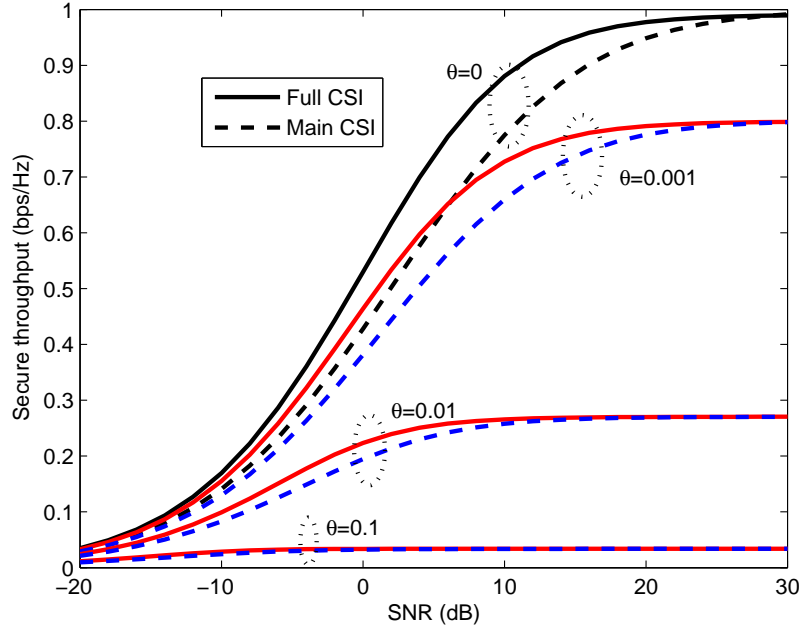


Fig. 6. The effective secure throughput vs. SNR in the Rayleigh fading channel with $\mathbb{E}\{z_E\} = \mathbb{E}\{z_M\} = 1$. $\gamma = 1$.

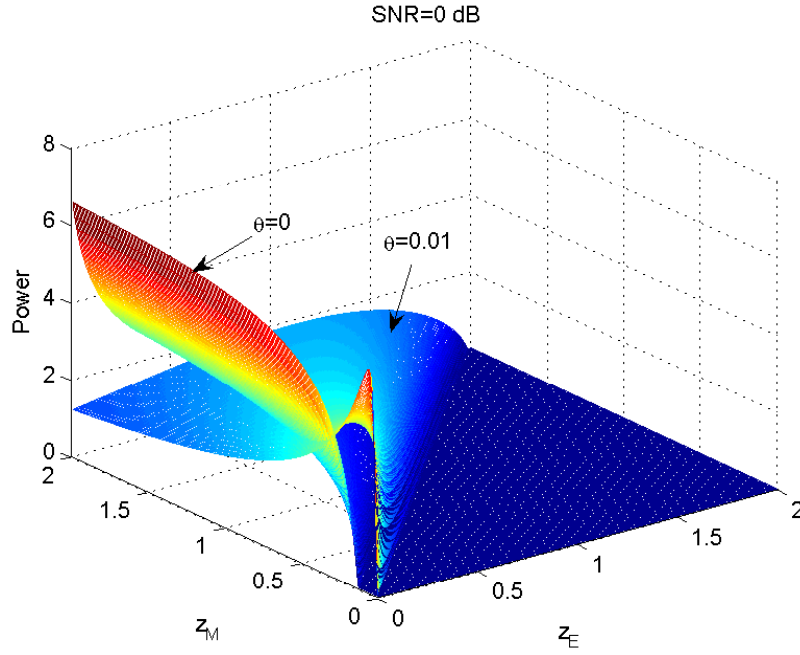


Fig. 7. The power allocation for the full CSI scenario with SNR = 0 dB in the Rayleigh fading channel with $\mathbb{E}\{z_E\} = \mathbb{E}\{z_M\} = 1$. $\gamma = 1$.

power is allocated for transmission when $z_M < z_E$ which is expected under the assumption of equal noise powers, i.e., $N_1 = N_2$. We note that when $\theta = 0$ and hence there are no buffer constraints, opportunistic transmission policy is employed. More power is allocated for cases in which the difference $z_M - z_E$ is large. Therefore, the transmitter favors the times at which the main channel is much better than the eavesdropper channel. At these times, the transmitter sends the information at a high rate with large power. When $z_M - z_E$ is small, transmission occurs at a small rate with small power. However, this strategy is clearly not optimal in the presence of buffer constraints because waiting to transmit at a high rate until the main channel becomes much stronger than the eavesdropper channel can lead to buildup in the buffer and incur large delays. Hence, we do not observe this opportunistic transmission strategy when $\theta = 0.01$. In this case, we note that a more uniform power allocation is preferred. In order not to violate the limitations on the buffer length, transmission at a moderate power level is performed even when $z_M - z_E$ is small.

V. CONCLUSION

In this paper, we have investigated the fading broadcast channels with confidential messages under statistical QoS constraints. We have first defined the effective secrecy throughput region and proved the convexity of this region. Then, optimal power control policies that achieve the points on the boundary of the throughput region are investigated. We have determined the conditions satisfied by the optimal power control policies. In particular, we have identified an algorithm for computing the optimal power allocated to each fading state using the optimality conditions. When the broadcast channel is reduced to the wire-tap channel with zero common message rate, we have investigated two types of optimal power allocation policies that maximize the effective secure throughput. In particular, we have noted that the transmitter allocates power more uniformly instead of concentrating its power for the cases in which the main channel is much stronger than the eavesdropper channel. By numerically comparing the obtained effective secure throughput, we have shown that as QoS constraints become more stringent, the benefits of incorporating the CSI of the eavesdropper channel in the power control policy diminish.

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